Link Scheduling in Cooperative Wireless Networks

Antonios Argyriou

Abstract

In this paper we propose link scheduling algorithms for a wireless network that employs different modes of cooperation at the physical layer (PHY). In addition to a direct transmission, a cooperative transmission through a relay and cooperative transmission through physical layer network coding (PLNC) can also be employed by a network node. The physical interference model is extended to reflect the aggregate signal to interference and noise ratio (SINR) at a node for all the cooperative schemes. With the proposed interference model not all concurrent transmissions are considered as destructive but their precise impact depends on the selected mode of cooperation.

Armed with the new interference model, and for a setup that involves a wireless mesh network, first we consider the problem of optimal link pairing (OLP) where the goal is to identify the optimal pairs of nodes that can transmit with cooperative transmission or PLNC. Next, we consider the problem of shortest link scheduling (SLS) where the goal is to increase the number of transmissions in the same time slot. The performance evaluation reveals that when interference at the PHY is allowed through PLNC or with a cooperative protocol, the scheduling algorithm may need to increase interference rather than reduce so that performance is improved.

Index Terms

Link scheduling, packet scheduling, wireless networks, shortest link scheduling, interference, cooperative systems, physical layer network coding.

The author is with The Department of Computer and Communication Engineering, University of Thessaly, Volos, 38221, Greece.

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I. INTRODUCTION

The topic of link and packet scheduling in wireless networks had attracted in the recent years a significant amount of research efforts with significant results that may have practical implications in real deployments [1], [2]. Link scheduling consists of the selection and activation of particular point-to-point links of the wireless network at a specific time instant. Therefore, optimal link scheduling will allow more network nodes to transmit concurrently by minimizing interference. For link scheduling to take place there must be a way to quantify the relationships between active network nodes so as to accurately evaluate the impact of a scheduling decision on other network nodes. The protocol and the interference models have been used extensively for this purpose [3]. The majority of works that are reviewed later, build on top of the later of the two aforementioned models since it has been experimentally validated [4]. Furthermore, existing scheduling algorithms that are based on the interference model assume that the network is decomposed into single transmitter-single receiver point-to-point links. Naturally, all point-to-point transmissions if they happen concurrently they interfere which means that the require careful scheduling.

However, in wireless networks today, not all transmissions can be considered equivalent which means that they cannot be treated similarly by a scheduling algorithm. We present two cases that arise in modern wireless networks and may require different treatment of wireless links. The first case comes from the observation that in the recent years there is a shift towards changing the point-to-point paradigm with the aid of helping nodes, usually named relays [5], [6]. A relay in wireless network essentially alters the point-to-point communication link between two nodes since it involves a third node. In this case the forwarding of a signal from the relay is an integral part of the primary transmission of the initial source since the destination node decodes at the PHY jointly the signal from the source and the relay. For example in Fig. 1 we see that when node S_1 selects node R_3 to be the cooperative relay that forwards its signal to D_1, the interference generated by this ”composite” transmission consists of the interference from both S_1, and R_3 although in different time slots. The second case is that the treatment of all transmitters as sources of interference does not have to be necessarily the case. It is possible that multiple and concurrently transmitting users are not destructively interfering but instead they improve the system throughput. This is possible with a different type of cooperation and is

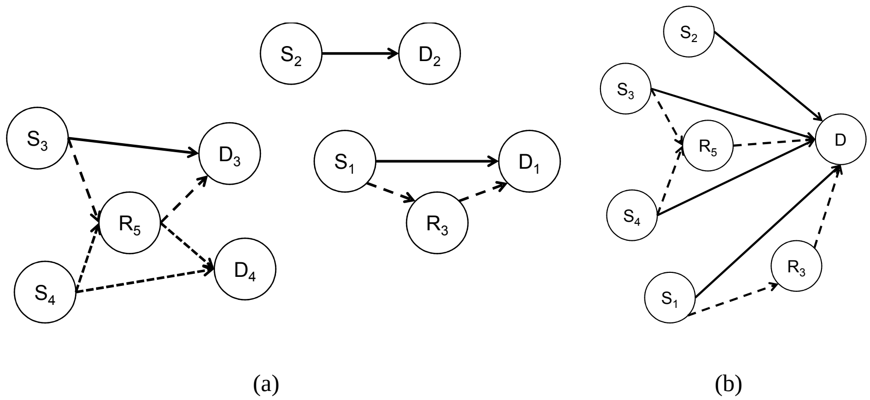


Fig. 1. Example of distributed wireless mesh network (a) and centralized uplink scenario (b) that allows multiple PHY cooperative packet transmission schemes. In these networks, the senders can communicate directly with their respective destination(s). When the cooperative transmission modes are employed, link scheduling must account for more point-to-point transmissions (shown with dashed lines).

usually referred as physical layer network coding (PLNC) [7]. With PLNC nodes cooperate and exploit both interference and a-priori information available at the involved nodes. To continue our previous example in Fig. 1, with cooperative PLNC (CPLNC) the transmissions from three nodes will generate interference, namely S_3, S_4, R_5. Overall, as it can be seen in Fig. 1, three communication modes between the wireless network nodes are possible. In this context, link scheduling has to be able to identify if for a pair links their concurrent activation is indeed a source of interference for each other or if it is beneficial for the sum-rate. Thus, the functionality of link scheduling has to be extended in order to select the suitable transmission mode and also the optimal relay.

In this paper, we investigate link scheduling for a wireless network that exploits the presence of relays, and it also allows users to employ either cooperative transmissions (named COOP for the rest of this paper) or a CPLNC-based protocol. The later scheme means that the physical layer (PHY) allows packet transmissions to interfere between multiple senders while these transmissions should be encouraged rather than deterred if they can increase the sum-rate of the two users. To address the problem of link scheduling in this setting, first we calculate the conditions for allowing the cooperative interference of multiple packets to occur under PLNC by defining a new interference model. The proposed interference model considers the produced interference of the composite COOP of PLNC transmission that require the activation of more

than one point-to-point links. Then, we propose a centralized heuristic scheduling algorithm based on this result. The performance results provide significant insights for link scheduling schemes that employ different cooperative transmission modes. We observed that unlike the standard approach for link scheduling in a non-cooperative network where weak users are bunched together while strong users transmit one at a time [1], when COOP or PLNC are employed, users with arbitrary differences in the transmitted signal strength may be the optimal choice for concurrent transmission. Depending on the received signal at the available relays and the final destinations, it is possible that the optimal choice is COOP or even the concurrent transmission under PLNC. Another interesting result is that increased interference does not always result into lower performance of link scheduling since the algorithm may select a suitable second node for a CPLNC transmission that leads to high sum-rate. Therefore, the optimality of scheduling decisions depends on several parameters and is not straightforward to define scheduling policies by roughly separating the users to weak and strong or classify a concurrent transmission as always harmful.

A. Paper Organization

The rest of the paper is organized as follows. First, in Section II we present an overview of the related works. The system model and a brief description of the used cooperative schemes can be found in Section III. The interference model that accounts for COOP and CPLNC is described in Section IV. In Section V we describe the optimal link pairing problem, the algorithm, and representative results. Next, in Section VI we present in detail the problem formulation and the proposed scheduling algorithm. Section VII presents simulation results, while Section VIII presents conclusions and provides some directions for future work. The performance analysis for proposed algorithm is presented in the Appendix.

II. Related Works

Identifying conflicting relationships between network nodes is central to link scheduling problems. The edge-based idea of the conflict graph for modeling interfering relationships under the physical interference model was introduced in [8]. In this conflict graph, that we also adopt but extend in this paper, a node is created for each point-to-point link in the wireless network, and a weight is created between two of the aforementioned nodes when the associated links interfere

with each other. Now the resulting interference can be quantified with two well-known models. The protocol model defined in [3] distinguishes the links in two types, namely the ones that interfere and the ones that do not. However, this approach does not match well with real wireless networks and the physical layer interference model, proposed in the same work, is usually chosen instead. More recently several link scheduling schemes based on the physical interference model have been presented [9], [10], [11], [12]. In [9] Brar *et. al* investigate the idea of link scheduling for static multi-hop mesh networks and they proposed a centralized polynomial-time heuristic algorithm. In [10] Wang *et. al* introduced the idea of the interference number that corresponds to the amount of interference generated in the network by a communication going on along a certain link and they exploit it for simplifying the scheduling algorithm. Concurrent transmission from multiple but non-interfering users has also been considered by Xiong *et. al* [11]. In the aforementioned work the purpose of the scheduling algorithm was to ensure that under the interference model, the involved nodes either maintain a target transmission rate or maximize their throughput. An important assumption was that interference was treated as noise. More recently in [12] Blough *et. al* were able to derive deterministic bounds for the length of the schedule under the physical interference model.

One topic that was not the focus of the previous works, was the extraction of useful information from interfering signals. One of the most interesting contributions towards this different avenue was presented recently by Lv *et. al* where the authors considered a receiver that employs successive interference cancellation (SIC) [13]. The authors introduced a greedy algorithm to construct schedules of bounded length for ad-hoc networks that take into account the fact that the receiver employs SIC for decoding the desired packet. In the same paper the authors defined an extended version of the interference model with receivers that employ SIC. The most important feature of this scheme is that it accounts for the secondary interference in case of SIC which is the interference that it does not act directly on the desired signal, but on a correlated signal that is detected with SIC and propagates to the detection of the desired signal. Multiple packet reception (MPR) is also a method for extracting infromation from interfered signals. Previous works on link scheduling and MPR focused on the design of a distributed MAC [14] and also the combination of MPR with joint routing and packet scheduling [15]. However, none of these works considered cooperation and also precise link scheduling under the realistic physical interference model.

Link scheduling and the impact of relays has been considered by Hong *et. al* in [16]. In that work the authors considered relays as a mechanism to aid in multi-hop communication and not for improving the performance of the PHY. Then the problem of link scheduling was considered in a formulation that minimizes interference across the multiple hops. Also recently Goussevskaia and Wattenhofer analyzed the complexity of scheduling wireless links in the physical interference model with a single relay having PLNC capability [17]. The authors considered a canonical network with a specific structure and traffic flow that is suitable for a type of PLNC that is used with bidirectional traffic. Xue *et. al* in [18] considered opportunistic scheduling for two-way physical layer network coding in very small line networks with bidirectional traffic and again a single relay node. The particular topic of packet scheduling has also been considered for networks that employ network coding but only in its digital form where complete packets are algebraically coded [19], [20].

III. System Model

We study the relay network model where a set of $\mathcal{S} = \{S_1, S_2, ..., S_N\}$ senders/users want to communicate with an equal number of destination nodes that are denoted as the set $\mathcal{D}$ with the assistance of a set $\mathcal{R} = \{R_1, R_2, ..., R_M\}$ of M relays. The complete network is modeled with a directed graph $F(\mathcal{U}, \mathcal{V})$, where $\mathcal{U}$ and $\mathcal{V}$ are the set of point-to-point directional links, and the set of nodes, respectively ($\mathcal{V} = \{\mathcal{S}, \mathcal{D}, \mathcal{R}\}$). Therefore, the number of point-to-point links in the graph is N if direct transmission is used. We also use the conflict graph of F that is defined as $G(\mathcal{U}, \mathcal{V})$, and contains the interfering relationships among the N links in the network. Each vertex in the conflict graph represents a wireless link in the network, and there is an edge between two vertices if and only if the links represented by the vertices conflict (i.e. they interfere with each other and simultaneous transmission is impossible). On the other hand, a clique in the conflict graph represents a group of links that cannot transmit concurrently, and hence they must access the channel exclusively.

The definition of a link in this paper is extended and may involve more than two nodes. We refer explicitly to a link between two nodes as a point-to-point link. This link corresponds to one sender i and one receiver i and is denoted as l_{ii} (where the two subscripts indicate the transmitter and the receiver of the point-to-point link). When the PLNC mode is selected, two sources i and j, one relay r, and two destinations i, j are involved. We call this the *CPLNC link* $l_{(i,j,r)}$ and it

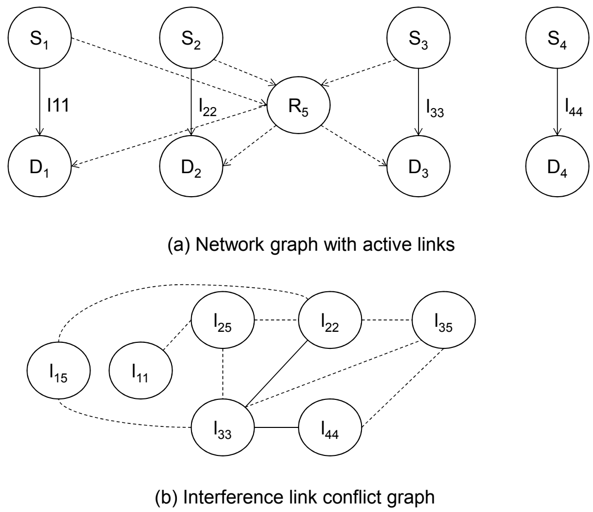


Fig. 2. Example network graph (a) and the corresponding link conflict graph (b). With solid lines are denoted the point-to-point links that belong in $\mathcal{U}$ while links with dashed lines denote the additional point-to-point links that belong in $\mathcal{U}^{'}$.

is decomposed into several point-to-point links as follows. If j is the second sender, and r is the relay, the additional links from both senders are denoted as l_{jj}, l_{ir}, l_{jr}. The associated relay links that are active during the forwarding phase are denoted as l_{ri}, l_{rj}. Therefore, we define the extended group of point-to-point links as $\mathcal{U}' \triangleq \mathcal{U} \cup \{l_{kr}, l_{rl}, \forall (k,l) \in \mathcal{N} \times \mathcal{N}$ and $\forall r \in \mathcal{R}\}$. It consists of all the combinations of source/relay and relay/destination links. Similarly we define the *COOP link* that consists of three point-to-point links.

A. Description of the CPLNC PHY

While cooperative protocols at the PHY have been widely investigated, the idea of allowing transmissions to be mixed over the air requires a different protocol and decoding algorithms. In this paper we consider a simple protocol for demonstrating easier the modeling concept and the scheduling algorithm. With the CPLNC cooperation two nodes transmit simultaneously in one time slot, and in the next slot a relay forwards the mixed signal without decoding it locally. The premise is that with two concurrently transmitting users the number of required time slots is reduced by half when compared to the cooperative transmission. This means that if the BER performance with CPLNC can be reduced significantly when compared with COOP, then for a specific SNR regime throughput can be higher [21], [22].

For simplifying the notation and the explanation of the basic protocol and decoding algorithm here, we use again the example in Fig. 1 to demonstrate this process. Let us denote the transmitted packets/signals as x_A and x_B. The transmitted signals in this example originate from S_3 and S_4 and are received by the intended receivers D_3 and D_4, and also by the relay R_5. For expressing mathematically our algorithm let us denote with $\mathcal{X}_\mathcal{A}, \mathcal{X}_\mathcal{B}$ the fixed symbol dictionaries that depend on the modulation scheme that the two senders use. Let also P denote the power allocated at each sending node, while g_r is the power allocation factor at the relay r. Finally let also the noise be denoted by $w \sim \mathcal{CN}(0, \sigma^2)$. From Fig. 1 we can see that the direct signal that will be received at the destination D_3 is

$$y_{D_3} = \sqrt{P} h_{S_3,D_3} x_A + \sqrt{P} h_{S_4,D_3} w_B + w_3, \tag{1}$$

In the forwarding phases the relay r broadcasts the received signals that are transmitted by applying first a power amplification factor g_r so as to maintain the power constraint [23]. The power gains are given as

$$g_r = \sqrt{\frac{P_r}{\sum_{s=1}^{N} P_s |h_{s,r}|^2 + \sigma^2}}. \tag{2}$$

So the received signal at the destination D_3 now is

$$\begin{aligned} y_{D_3,R_5} &= \sqrt{P} h_{S_3,R_5} h_{R_5,D_3} g_r x_A + \sqrt{P} h_{S_4,R_5} h_{R_5,D_3} g_r x_B \\ &+ h_{R_5,D_3} g_r w_5 + w_3. \end{aligned} \tag{3}$$

Now D_3 combines the direct and relayed signals with a single ML demodulation step [21]. Before this process takes place, the receiver identifies the packet preamble that is contained in each version of the two aforementioned signals and then it aligns them at the symbol-level [21], [24].

IV. Interference Model

From the previous discussion it is obvious that in our system not every simultaneous transmission is harmful. The way two transmissions interfere is unlike the case of the point-to-point transmission. Interference depends on the selected mode of cooperation since it can corrupt the signal received at the destination, the signal at the relay, or the relayed signal at the destination during the final forwarding phase. These observations pave the way for deriving the interference model for the cooperative transmission modes.

A. SNR Expressions for the Cooperative Protocols

The general case of cooperative systems, the transmitter may select to use cooperative transmission when a desired rate is not met with a direct transmission. However, without loosing generality we assume that in the proposed system a transmission can be selected, whether it is CPLNC, COOP, or Direct, if it can achieve higher SNR than the other transmission modes. Now let us consider that the channel bandwidth is W, the transmitter power P, additive white Gaussian noise (AWGN) with zero mean and variance σ^2, and $\gamma_i = |h_i|^2$. If we assume Rayleigh block fading channels where the attenuation is considered constant throughout the transmission of a single frame then the receiver SNR for two nodes transmitting under the Direct mode is:

$$SNR_i^{dir} = \frac{P\gamma_{i,i}}{\sigma^2}. \tag{4}$$

On the other hand, the SNR of the cooperative transmission COOP that occurs in two orthogonal time slots as in the example in Fig. 1 will be [23]:

$$SNR_{i,r}^{coop} = \frac{P\gamma_{i,i}}{\sigma^2}\frac{P\gamma_{i,r}\gamma_{r,i}g^2}{\sigma^2(1+\gamma_{r,i}g^2)} \tag{5}$$

Now we present the SNR of the CPLNC transmission with the help of relay. This SNR for two interfering transmissions incorporates the overheard information that is used for decoding the respective signals/packets at each receiver. Let the transmit power at the two senders be P_i and P_j. Then, the SNR can be expressed at D_i if S_i is transmitting and S_j is interfering [21] as

$$\begin{aligned} SNR_{i,j,r}^{cplnc} &= \frac{P_i\gamma_{i,i}}{\sigma^2} + \frac{P_j\gamma_{j,i}}{\sigma^2} + \frac{P_i\gamma_{i,r}\gamma_{r,i}g^2}{\sigma^2(1+\gamma_{r,i}g^2)} \\ &+ \frac{P_j\gamma_{r,i}\gamma_{j,r}g^2}{\sigma^2(1+\gamma_{r,i}g^2)} + \frac{P_iP_j\gamma_{i,i}\gamma_{r,i}\gamma_{j,r}g^2}{\sigma^4(1+\gamma_{r,i}g^2)} \end{aligned} \tag{6}$$

And so for node i to decode the packet from sender i at rate R_D regardless of the transmission mode it must be

$$SNR \geq 2^{R_D} - 1 \triangleq \beta_i, \tag{7}$$

regardless of the transmission mode used. The above expressions are impractical to be used for real-time estimation, especially for a network-wide link scheduling scheme. This is the reason we seek a simpler model. Under path loss all the involved channels are simply characterized only by the distance between the transmitter and the receiver and so it is for example that $\gamma_{i,r} = 1/d_{i,r}^a$, an assumption that we follow for the rest of this document.

B. SINR for Cooperative Multi-Phase Transmission Modes

In the section we extended the SNR expressions to signal-to-noise-plus-interference ratio (SINR) by including the interference term. Each link can sustain only a certain amount of interference before the SINR falls below the allowed threshold. This can be quantified by the tolerance of the link l_{ii} [25] and it is denoted with $\mathcal{I}$. For a CPLNC scheme, and even more generally for a scheme that employs cooperation, the interference that can be allowed before the packet becomes non-decodable has to be calculated differently. To calculate interference in cooperative wireless links we have to define first $\mathcal{A}_t$ as the group of links that are activated during time slot t regardless if they are senders or relays. Then the aggregate interference that is accumulated over a node i during that slot t is defined as

$$I_{i,t}^{dir} = \sum_{l_{mk} \in \mathcal{A}_t / \{l_{ii}\}} \gamma_{m,i} P_m, \tag{8}$$

where l_{mk} denotes other activated links during the same time slot t, and k can correspond to an arbitrary node (relay or destination). P_m being the transmit power. Since the two cooperative modes considered in this paper involve the transmission of the packet in two phases (broadcast and forwarding) and also the reception of the packet by a relay, three instances of the above metric have to be calculated. During the broadcast phase of the CPLNC or COOP modes, the total interference at node i is denoted as $I_{i,b}$, and can be analytically expressed as

$$I_{i,b}^{cplnc} = \sum_{l_{mk} \in \mathcal{A}_t / \{l_{ii}, l_{jj}, l_{ir}, l_{jr}\}} \gamma_{m,i} P_m, \tag{9}$$

where each node m and the associated link l_{mk} that belongs in the activation set $\mathcal{A}_t$, transmits and interferes at i by $\gamma_{m,i} P_m$. Note that when the CPLNC mode is selected for the pair of nodes i, j, the undesired interference at node i is induced by all links besides link l_{jj} that participates in the CPLNC transmission. Similarly with the previous we define $I_{i,f}$ and $I_{r,b}$ that correspond to the aggregate interference at destination i during the forwarding phase and the aggregate interference at the relay r during the broadcast phase:

$$I_{i,f}^{cplnc} = \sum_{l_{mk} \in \mathcal{A}_{t'} / \{l_{ri}, l_{rj}\}} \gamma_{m,i} P_m, \tag{10}$$

$$I_{r,b}^{cplnc} = \sum_{l_{mk} \in \mathcal{A}_t / \{l_{ii}, l_{jj}, l_{ir}, l_{jr}\}} \gamma_{m,r} P_m \tag{11}$$

From the above definitions for the aggregate interference induced on a CPLNC link, we see that is more demanding for this parameter to be calculated when compared with point-to-point direct transmissions [25].

Now the SINR of the CPLNC transmission is revised given the aggregate interference formulas. This equation is extended for a node i if another node j is transmitting with CPLNC through relay node r:

$$\begin{aligned} SINR_{i,j,r}^{cplnc} &= \frac{P\gamma_{i,i}}{I_{i,b}+\sigma^2} + \frac{P\gamma_{j,i}}{I_{i,b}+\sigma^2} \\ &+ \frac{P\gamma_{i,r}\gamma_{r,i}g^2}{\sigma^2+I_{i,f}+(I_{r,b}+\sigma^2)\gamma_{r,i}g^2} \\ &+ \frac{P\gamma_{r,i}\gamma_{j,r}g^2}{\sigma^2+I_{i,f}+(I_{r,b}+\sigma^2)\gamma_{r,i}g^2} \\ &+ \frac{P^2\gamma_{i,i}\gamma_{r,i}\gamma_{j,r}g^2}{(I_{i,b}+\sigma^2)[\sigma^2+I_{i,f}+(I_{r,b}+\sigma^2)\gamma_{r,i}g^2]} \end{aligned} \tag{12}$$

From the previous discussion we see that the aggregate interference is not simply the additional scalar term that should be added in the denominator of the SNR expression (see (4)), but it is a vector of the three individual aggregate interference values calculated before:

$$\vec{I_i} = [I_{i,b} \quad I_{i,f} \quad I_{r,b}] \tag{13}$$

To complicate things even more, the tolerance of the node i is a function of the individual tolerances of the participating nodes during each of the phases, and also a function the participating node j:

$$\vec{\mathcal{I}_i} = f([\mathcal{I}_{i,b} \quad \mathcal{I}_{i,f} \quad \mathcal{I}_{r,b}], S_j) \tag{14}$$

In the above, $\mathcal{I}_{i,b}$ is the maximum interference that node i can accept during the broadcast phase before the cooperative transmission becomes undecodable. However, this depends on both $\mathcal{I}_{i,f}, \mathcal{I}_{r,b}$. From the last SINR expression, it is important to understand that a different level of interference can be allowed in the broadcast and forwarding phases. The interference induced during the broadcast phase affects the tolerance of the nodes that participate in the forwarding phase. Therefore, these phases cannot be seen as decoupled. To avoid the complexity of such an approach our solution algorithm that we present later is utilizing a heuristic rule derived from the generic definition above. Besides the apparent complication that arises from (14), an important detail can allow the implementation of this metric with more flexibility. *By adjusting*

the interference (higher or lower) in one phase, the model allows this decision to be counteracted by adjusting interference (lower or higher respectively) during another phase in order to maintain the SINR at the desired level. This is a another aspect of the model that the proposed scheduling algorithm exploits.

V. Link Activation for maximum PLNC Network Throughput without Interference

First, we investigate a unique aspect of the proposed system and presented interference models that arises from the use of the cooperative modes. We adopt the cooperative SNR model without considering interference. The goal in this case is to maximize the receiver SNR for all the nodes in the complete network subject to SNR conditions for each node. The uniqueness of the problem is that the use of the COOP and CPLNC transmission modes results in a more complex potential solution since pairs of links that should be activated simultaneously have to be identified. We call this the optimal link pairing problem (OLP) and when only the CPLNC mode is allowed to be used it can be formally written as:

$$
\begin{aligned}
&\max \sum w_i SNR_{i,j,r}^{cplnc} + w_j SNR_{j,i,r}^{cplnc} \qquad (15)\\
&SNR_{i,j,r}^{cplnc} \geq \beta_i,\\
&SNR_{j,i,r}^{cplnc} \geq \beta_j,\\
&l_{ii}, l_{jj}, l_{ir}, l_{jr}, l_{ri}, l_{rj} \in \mathcal{A}\\
&w_i, w_j > 0
\end{aligned}
$$

The activation set $\mathcal{A}$ includes all the links of all the CPLNC transmissions. The traffic demands w_i, w_j at each source node must be positive. The above formulation means that the pair of links that should be allowed to transmit simultaneously, should be the one that maximizes the sum rate.

A. Exhaustive Link Pairing (ELP) Algorithm

The optimal solution to the previous problem requires each pair of node candidates to be tested, since the node location is the one factor that determines whether CPLNC or COOP will be effective. We also know that scheduling over all the links of the conflict graph is known to

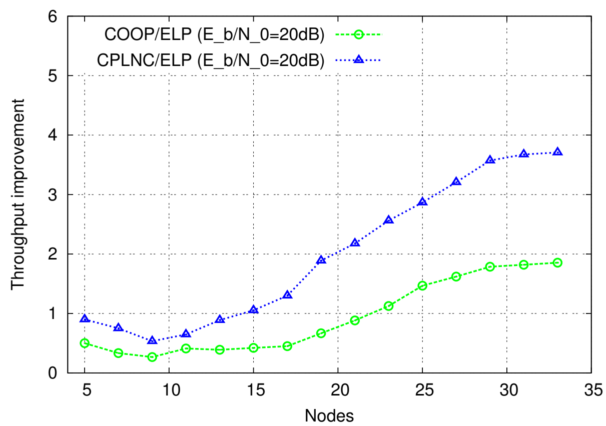


Fig. 3. Results for the exhaustive link pairing algorithm for different number of senders.

be NP-hard [8], [26]. Thus, we cannot design an optimal scheduling scheme over the conflict graph within a polynomial time since the previous problem formulation is an extension of the link scheduling problem with point-to-point links. Even though we do not envision the previous approach as a realistic solution we think that it can serve as an reference point for other heuristic solutions. The objective of the algorithm is to identify the pairs of links that should be activated simultaneously so that SNR and throughput are maximized. At this stage for simplicity we assume that one relay is used while a brute force exhaustive search is implemented in order to identify the upper bound performance of our scheme. The brute-force algorithm is designed by using the following theorem.

Theorem 1. *Let F be a communication graph, $\mathcal{U}$ the set of point-to-point links and G be its corresponding link conflict graph. Let also L be the ordered list of all the possible CPLNC links from higher to lower SNR at the respective destination. Under the assumption that only two users transmit in a single time slot, the selection of a CPLNC transmission between nodes i and j of links $l_{ii}, l_{jj} \in \mathcal{U}$ with the highest rate achievable rate (the top of L), is always the optimal choice for maximizing network throughput.*

Proof: The result to show is that when two selected links selected from $\mathcal{U}$ are scheduled together with CPLNC, and both the vertices are removed from the conflict graph G, if the ordering in L is followed, this choice does not remove the ability from the algorithm to select a

better combination of links to schedule with CPLNC (the removal of them does not reduce the opportunities).

Consider a representative ordering of the aggregate SNR when three nodes $k, m, n \in \mathcal{U}$ are paired together with CPLNC, and let $SNR_{n,k} < SNR_{k,m} < SNR_{m,n}$, i.e. they are ordered in increasing order. Assume that link l_{nn} is scheduled with link l_{mm} with CPLNC since this is the maximum SNR/rate choice. The sum-rate of this communication is given by (12). If l_{mm} and l_{nn} are scheduled together, then another node k cannot be scheduled with either l_{mm} or l_{nn}. But the choices of $SNR_{k,m}$, $SNR_{k,n}$ were already rejected from the initial ordering. Also the choice if $SNR_{l,m}$ would also be in the global order but it was not selected initially because it provided lower rate. ■

B. Results for the ELP Algorithm

We present now a few representative results for the previous algorithm. In these simulations, we randomly generate a number of wireless nodes uniformly in a square 10×10 unit region. The transmission range is randomly drawn from 2 to 4 units. The traffic originates from one sender and is directed towards one destination without using multihop communication. The node number varies from 5 to 32. We examine the performance of ELP when only the CPLNC PHY was used and also when the use of ELP was combined with COOP (in this case the number link pairs that are tested is smaller since it involves only an additional relay). The average of the simulations over all the 1000 randomly generated networks are plotted. The results can be seen in Fig. 3 for average channel SNR of 20dB. It is important to see the ELP algorithm can identify the optimal link pairs leading to a throughput improvement of nearly 80% over the COOP/ELP scheme. It is crucial to see here that as more nodes are introduced throughput is rapidly increasing since more options exist for the ELP. This is possible until a certain point where the throughput gain saturates and remains the same for increasing number of nodes. The results are very promising for following up with scheduling algorithm that can pack more transmissions per time slot.

VI. Shortest Link Scheduling (SLS)

Armed with a model for the precise relationship between the aggregate interference and the SINR of the cooperative transmissions, we can proceed and define the desired optimization problem. One important objective of link scheduling is to minimize the total duration of the

TABLE I

ALGORITHM NOTATION SUMMARY

Notation	Explanation
I_i	interference at node i
$I_{i,t}$	interference at node i during phase/slot t
$\mathcal{I}_{i,t}$	maximum interference at node i during phase/slot t
$\mathcal{A}_t$	group of links scheduled in slot t
$\mathcal{A}_{s1,t}$	group of CPLNC source links scheduled in slot t
$\mathcal{A}_{s2,t}$	group of COOP source links scheduled in slot t
$\mathcal{A}_{s3,t}$	group of Direct source links scheduled in slot t
$\mathcal{U}$	group point-to-point links that require scheduling
$\mathcal{U}'$	extended group of point-to-point links that includes relays
β_i	PHY signal decoding threshold
T	schedule length in slots

scheduled transmissions which is the shortest link scheduling (SLS) problem. In this work SLS should be accomplished by selecting the most appropriate transmission mode and the most appropriate relay during each slot t, while users should be allowed to transmit if they do not interfere and make undecodable an already scheduled CPLNC, COOP or Direct transmission. Therefore, scheduling has to be performed both across space (different relays and senders) and across time so as to increase the utilization of the wireless medium. To accomplish the above we define as the problem objective the minimization of the duration of the complete schedule in terms of slots, by maximizing the number of concurrent PLNC, COOP or Direct transmissions. Let L_t be the number of point-to-point links transmitting in slot $t \in T$ and $\mathcal{A}_t$ the link activation set during this slot. The activation set includes both relayed transmissions and broadcasts from the initial senders. The aggregate undesired interference that node i receives during slot t depends on the number of the other transmitting links which is $L_t - 1$. Thus, the goal is to maximize L_t

subject to the interference constraints:

$$\begin{aligned}
&\max L_t \quad \forall t \in T \qquad (16)\\
&SINR^{cplnc}_{i,j,r}(I_{i,b}, I_{i,f}, I_{r,b}) \geq \beta_i,\\
&SINR^{cplnc}_{j,i,r}(I_{j,b}, I_{j,f}, I_{r,b}) \geq \beta_j,\\
&\forall\ l_{ii}, l_{jj}, l_{ir}, l_{jr} \in \mathcal{A}_{s1,t}\ \&\ l_{ri}, l_{rj} \in \mathcal{A}_{r1,t'}\\
&SINR^{coop}_{i,r}(I_{i,b}, I_{i,f}, I_{r,b}) \geq \beta_i,\\
&l_{ii}, l_{ir} \in \mathcal{A}_{s2,t} \quad l_{ri} \in \mathcal{A}_{r2,t''}\\
&SINR^{dir}_{i}(I_{i,b}) \geq \beta_i,\\
&l_i \in \mathcal{A}_{s3,t}\\
&\mathcal{A}_t = \mathcal{A}_{s1,t} \cup \mathcal{A}_{s2,t} \cup \mathcal{A}_{s3,t} \cup \mathcal{A}_{r1,t} \cup \mathcal{A}_{r2,t}
\end{aligned}$$

In the above we distinguish the link activation set $\mathcal{A}_t$ into $\mathcal{A}_{s1,t}$, $\mathcal{A}_{s2,t}$, $\mathcal{A}_{s3,t}$ that are the activation sets for senders that use CPLNC, COOP, and Direct modes respectively. Also note that the relaying/forwarding phase can occur at any future slot t', t'' and that is we use the notations $\mathcal{A}_{r1,t'}, \mathcal{A}_{r2,t''}$ for the relay activation sets of the COOP of CPLNC transmissions. Similarly, in the current slot t it is possible that relaying phases from previous broadcast phases take place and they are denoted as $\mathcal{A}_{r1,t}, \mathcal{A}_{r2,t}$. Fig. 4 clarifies the behavior SLS in the time domain where it shows that while R_1 forwards the previously transmitted signals from S_1, S_2, nodes S_3 and S_4 broadcast simultaneously their own. Therefore, in this case both the initial signals/packets and the relayed packet are interfering.

A. *Greedy Heuristic Scheduling Algorithm for SLS*

Now we develop a centralized algorithm for solving the SLS problem presented previously. The novelty of the proposed algorithm is threefold. First, the algorithm completely decouples the scheduling of links during the broadcasting and forwarding phases that have to be traditionally carried out in consecutive slots. Second, a cooperative link that consists of several point-to-point links is treated as one interfering source for the remaining network. Third, the link scheduling algorithm is indirectly calculating the optimal transmission mode for each sender/receiver pair which traditionally has not been the task of link scheduling algorithm. The detailed operation

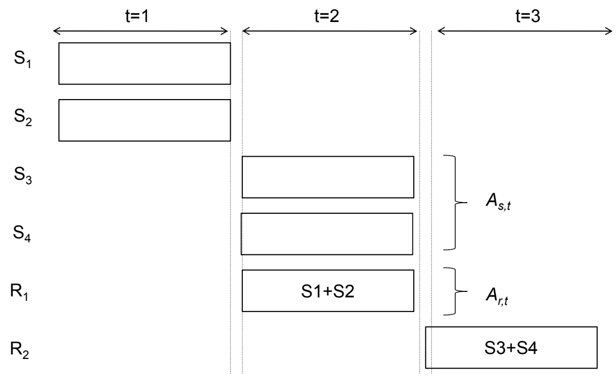


Fig. 4. Scheduling of cooperative links shown in the time domain. The transmitted signals from sources S_1 and S_2 are forwarded during the second time slot from relay R_1. At the same time two other sources also transmit.

of the greedy algorithm is presented next. Since the algorithm considers the scheduling of cooperative networks it is named Greedy cooperative SLS (*Greedy-CSLS*).

The *Greedy-CSLS* algorithm: Let $\mathcal{A}_t$ be the next scheduled link set (initially empty) to be constructed, and $\mathcal{Z}$ the set (initially empty) of unscheduled links that cannot be placed in $\mathcal{A}_t$. The greedy algorithm that is depicted in Fig. 7 proceeds as follows. First it generates $\mathcal{U}^{'}$ which as specified in our system model is the extended group of point-to-point links that includes also the relays. Then for each destination and each relay the algorithm calculates the aggregate interference induced by all the other links in the group of links $\mathcal{U}^{'}$ (lines 2-4 of the pseudoalgorithm). Note the use of CPLNC or COOP links means that in $\mathcal{U}^{'}$ we may have multiple source-relay and relay-destination point-to-point links that will receive different aggregate interference. The above has to be quantified so as to select the relay or source that is optimal and this is done through the link tolerance calculations.

In order to clarify better the process let us consider the example in Fig. 1 and let us calculate the interference. In this example $\mathcal{U} = \{l_{22}, l_{11}\}$ and $\mathcal{U}^{'} = \{l_{13}, l_{31}, l_{23}, l_{32}, l_{22}, l_{11}\}$. So the total aggregate interference $I_{i,\mathcal{U}'}$ for the three nodes that exist in the extended groups of links $\mathcal{U}^{'}$ is:

$$\begin{aligned} I_{1,\mathcal{U}'} &= P\gamma_{2,1} + P\gamma_{3,1} \\ I_{2,\mathcal{U}'} &= P\gamma_{1,2} + P\gamma_{3,1} \\ I_{3,\mathcal{U}'} &= P\gamma_{1,2} + P\gamma_{3,1} \end{aligned}$$

But what about the calculation of the link tolerance $\mathcal{I}$ of the composite links? The heuristic for the function f is chosen as follows. It is set to the minimum value of the individual node tolerances for each phase of the cooperative link transmission. More precisely consider $\mathcal{I}_{i,b}$ that is calculated by setting to zero the other interference terms in (12) for CPLNC. The same process is followed for calculating $\mathcal{I}_{i,f}$, and $\mathcal{I}_{r,b}$. So the heuristic version of (13) becomes now for COOP and CPLNC:

$$\mathcal{I}_i = \min(\mathcal{I}_{i,b}, \mathcal{I}_{i,f}, \mathcal{I}_{r,b}) \tag{17}$$

Therefore, the link tolerance calculations of the COOP mode for D_1 when the three transmission schemes are used is:

$$\begin{aligned}
\mathcal{I}_{1,b}^{coop} &= \arg_{I_{i=1,b}} \min SINR_{i,r}^{coop}\Big|_{I_{i=1,f}\leftarrow 0, I_{r=2,b}\leftarrow 0} \\
\mathcal{I}_{1,f}^{coop} &= \arg_{I_{i=1,f}} \min SINR_{i,r}^{coop}\Big|_{I_{i=1,b}\leftarrow 0, I_{r=2,b}\leftarrow 0} \\
\mathcal{I}_{2,b}^{coop} &= \arg_{I_{r=2,b}} \min SINR_{i,r}^{coop}\Big|_{I_{i=1,b}\leftarrow 0, I_{i=1,f}\leftarrow 0}
\end{aligned}$$

The result of this step in this example would provide all the link tolerance derivations $\mathcal{I}_1^{coop}, \mathcal{I}_2^{coop}, \mathcal{I}_1^{dir}, \mathcal{I}_2^{dir}, \mathcal{I}_1^{dir},$

The rationale for the above heuristic is simple. It sets the link tolerance of the composite link to that of the minimum among the three since the remaining two links can accept a higher level of interference and pose a smaller problem for the scheduling algorithm. The result of the above process can also be seen as the upper bound of the interference that the cooperative link can accept even if interference during the other phases is zero. The above process is executed in lines 5-11 of the algorithm.

When the tolerance $\mathcal{I}$ is calculated as we described above, a parameter that indicates the vulnerability for all links is derived. Link vulnerability is define in this paper as $\eta_i^{mode} = \frac{I_{i,\mathcal{U}'}}{\mathcal{I}_i^{mode}}$ and it shows that if a link under a specific mode has higher tolerance to interference it is less vulnerable. So the extended group of links in $\mathcal{U}'$ are reordered and placed in $\mathcal{L}$ according to the highest η which means the lowest destructive interference to tolerance ratio.

The next step for the algorithm is to check the first link in the above ordered data structure. The first link is the most sensitive link regardless of the transmission mode used and if it scheduled in one slot it is likely that fewer additional links will be scheduled in that slot. Assume now that this first link is the CPLNC link $l_{i,j,r}$. Given the selected link, the algorithm checks if any other CPLNC, COOP or point-to-point link can be added the same slot. The algorithm starts

from the first time slot. If time slot $t = 1$ is feasible for link $l_{i,j,r}$ (the total interference of the already scheduled transmitting links in that slot is less than its tolerance $\mathcal{I}_i^{cplnc}$), the value of the interference induced by all the links currently assigned in t and also of the additional interference by $l_{i,j,r}$ is stored (line 18 of the algorithm). Next the algorithm proceeds and evaluates the same aggregate interference $\forall t \in T$ (loop in line 15 of the algorithm) and then finally link $l_{i,j,r}$ is added in the slot that has the minimum aggregate interference. After the link has been scheduled from the list of ordered links $\mathcal{L}$ the algorithm removes the individual links l_{ii}^{dir} and l_{jj}^{dir},$l_{i,r}^{coop}$, $l_{j,r}^{coop}$ and also $l_{i,j',r}^{cplnc}$ and $l_{i',j,r}^{cplnc}$ since the related sender/destination node pairs i and j have been scheduled.

If the links cannot be added without violating the interference constraints, then the algorithm removes $l_{i,j,r}$ from the group $\mathcal{L}$ completely. *The reason is that the sending nodes also exist lower in the sorted link list $\mathcal{L}$ under different transmission modes and so they will have the chance to be scheduled with COOP or Direct modes that are more robust to interference.* Finally, if Direct transmission mode also adds significant interference and it also cannot be added then one more slot is added to T and then the algorithm tries again. As an optimization step, in the later case the algorithm selects the initiation of new scheduling attempts from the slot allocation that was found to be able to sustain the highest level of interference. In one recent work, the SLS problem was addressed by gradually reducing the maximum allowed schedule duration K, while the bisection method was used for reducing the length of the schedule [25]. This might also be an option for the proposed algorithm. Next we briefly discuss the complexity issues of the *Greedy-CSLS* algorithm.

Theorem 2. *Let F be a communication graph and G be its corresponding conflict graph, while w are the weights of each link representing the total traffic demand. The greedy algorithm Greedy-CSLS has $O(NT + N^2MT)$ time complexity.*

Proof: The number of ordered links in $\mathcal{L}$ is $N + \binom{N}{2}R$ for all the potential combinations of link pairs and relays. With an iterative algorithm $\binom{N}{2}$ can be calculated in $O(min(2, n{-}2))$, while with Pascal's triangle complexity is $O(n^2)$. The ordering of the links in the first step thus requires for a *quicksort* algorithm $O\big((N + \binom{N}{2}M)log(N + \binom{N}{2}M)\big) = O\big((N + N^2M)log(N + N^2M)\big)$ steps. Also $O(T)$ is the time complexity of checking in which slot to add a selected link out of the T. In the worst case, each of the $N + \binom{N}{2}M$ may be tested and each one may require

T tests. Thus the worst case time complexity for the second decoupled part of the algorithm is $O\big((N + N^2M)K\big) = O\big(NT + N^2MT\big)$.

■

VII. Performance Evaluation

A. Setup

Similar to related research works [8], [13], we compare the performance of the proposed scheduling algorithm to that of the baseline IEEE 802.11. Note that IEEE 802.11 is a CSMA MAC protocol and is not intended to take into account the link scheduling and interfering relationships. In addition, in order to be more fair we also present results for a system with the scheduling algorithm *Greedy-Physical* [9] where only direct transmissions are possible, and a system where *Greedy-CSLS* and both COOP and Direct are possible. With the notation CPLNC in the figures we denote the *Greedy-CSLS* algorithm where all transmission modes are possible. Of course it must be pointed out that this should not be seen as a comparison between the Direct transmission mode and the cooperative schemes since the later use relays. The goal is first to show the interplay between link scheduling algorithms and an underlying PHY that uses cooperation, and second to compare COOP with CPLNC that are different types of cooperation again under a link scheduling system.

B. Schedule Length Results for SLS under Greedy Scheduling

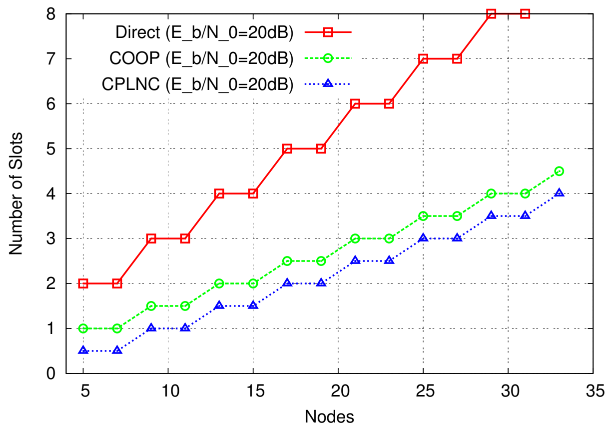
Fig. 5 depicts the schedule length of the different algorithms. In Fig. 5(a) and for SNR 20dB, the higher densities generate higher cumulative interference and so *GreedyPhysical* with the basic SINR physical model presents sliding performance gains. However, the algorithm is still able to schedule transmissions simultaneously which is better over a CSMA-based 802.11 system that would require a number of slots equal to the number of active links (number of nodes in the experiment divided by 2). This is not the case with *Greedy-CSLS* that exploits pairs of strongly interfering users for scheduling them concurrently as the density is increased. The CPLNC *Greedy-CSLS* performance benefits from the node density increase. For very high densities, there are multiple node pair candidates for creating CPLNC links. This approach effectively cuts the schedule length in half. Regarding the performance for lower channel quality presented Fig. 5(b) and for SNR of 15dB, the relative performance of all the algorithms when

compared together, they present a similar trend. However, the reduction in performance (longer schedule lengths) occurs at slightly higher node densities. The reason is that for lower channel quality the generated interference is lower by any concurrently scheduled transmission, which means that more transmissions can be packed together leading to shorter schedules. To reach the same level of aggregate interference a higher number of nodes must exist in the network. Finally, in Fig. 5(c,d) we can see the results for a different number of available relays. It is evident that the number of available relays has minimal impact of the slot reduction since it can only indirectly affect that parameter. More specifically in the cases where we observe reduction in the schedule length it is because the existence of more relays made possible slightly more CPLNC transmissions. With fewer relays, the optimal choices for CPLNC links are less which means that the COOP or Direct modes have higher probability of being selected.

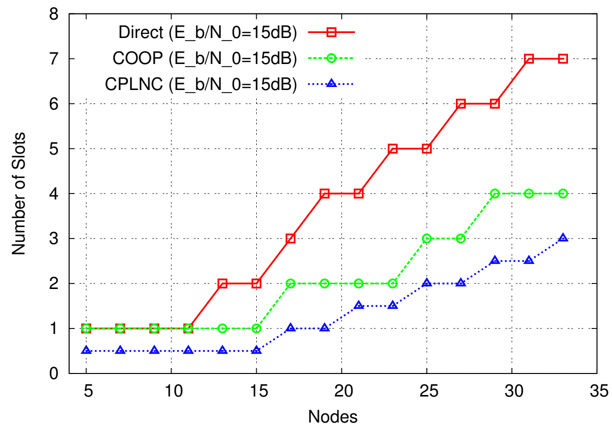
C. Throughput Results for SLS under Greedy Scheduling

The schedule length results are important but they do not reveal another important parameter that is system throughout. In the previous results we observed that for worse channel conditions the schedule length is reduced but these results do not give any hint about the throughput. Results for uniform backlogged traffic load of all the nodes and M=1 available relay in the network can be seen in Fig. 6. We can see that the system that employs all the cooperative modes including CPLNC is the most effective when compared to the other schemes as the number of network nodes is increased. Naturally as more nodes are introduced, the options for the creation of higher performance CPLNC links are more which means that a better throughput performance should be possible. However, this is the case for a subset of the nodes that can exploit more relays. For higher node density interference is increased across all the nodes even when the algorithm calculates better CPLNC links. Even though an optimal tradeoff with respect to the length of the schedule and the amount of allowed interference is achieved, still more nodes reduce the performance gradually. For a worse average channel quality of 15dB in Fig. 6(b) the performance trend is the same although the absolute values are lower due to higher PHY decoding failures.

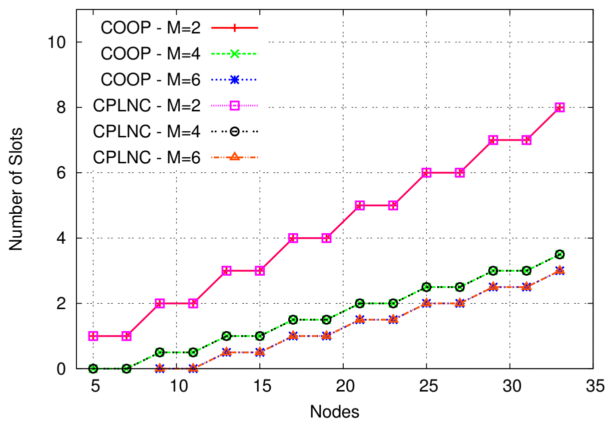
Now Fig. 6(c,d) depicts the performance of the link scheduling algorithms versus the number of network nodes for different number of available relays in the system. For the results in Fig. 6(c) where the average channel SNR is 20 dB, when more relays are available the probability that CPLNC or COOP can achieve higher performance is increased since more opportunities are



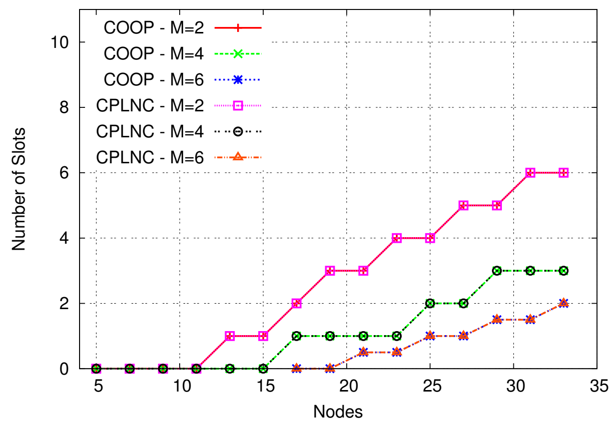
(a) Avg. channel SNR 25dB, $M = 1$



(b) Avg. channel SNR 15dB, $M = 1$



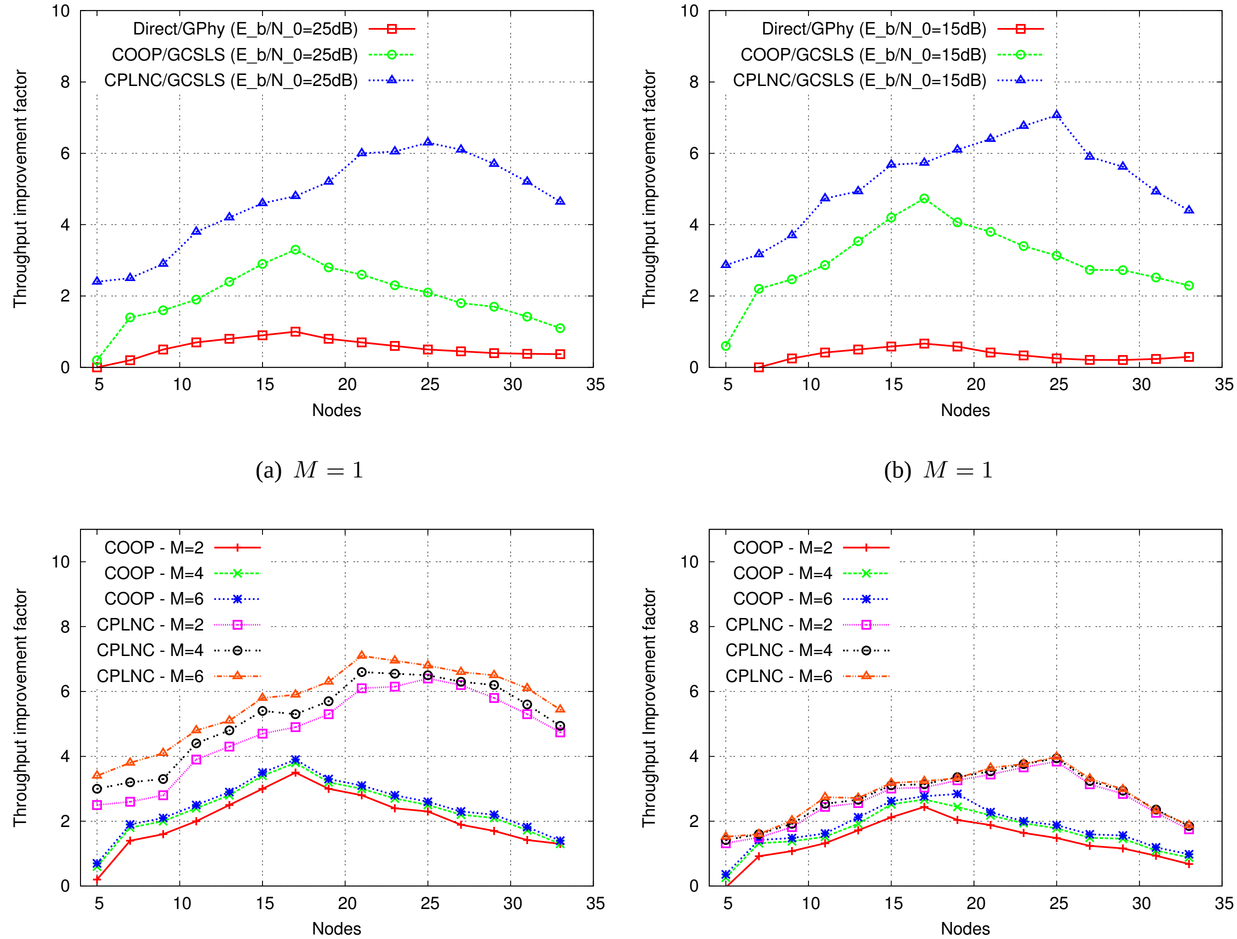
(c) Avg. channel SNR 25dB



(d) Avg. channel SNR 15dB

Fig. 5. Schedule length results for all the scheduling algorithms and for different number of senders.

possible with relays being distributed at different locations. However, our results show that this is possible up to a certain number of $M = 6$ relays and in the case that more relays become available the potential gain is minimized. This behavior depends primarily to the spatial arrangement of the relays that are more densely deployed as their number is increased and so minor differences in their location do not lead to significant rate increases. We expect that higher deployment areas will present this saturation effect at higher values of M. The results in Fig. 6(d) for channel SNR of 15dB present a similar trend but there is an important detail not obvious at first sight. That is the relative performance increase of COOP over the case of $M = 1$ relay is higher now. This is due to the more critical role that the relays play for COOP when the channel



(a) $M = 1$

(b) $M = 1$

(c) Average channel SNR 25dB

(d) Average channel SNR 15dB

Fig. 6. Throughput results for the greedy algorithm and for different number of senders and relays.

conditions are poorer.

VIII. CONCLUSIONS

In this paper we presented a greedy link scheduling algorithm suitable for wireless networks that support at the PHY both cooperative transmissions and superimposed signal transmissions under a PLNC protocol. The proposed algorithm is based on new interference model that does not assume that a single transmission is harmful for all other nodes in case cooperation is employed. More specifically concurrent transmissions may occur naturally and as part of the normal system operation defining thus a new type of a link that has to be handled differently from

the scheduling algorithm. Performance results indicate the significant benefits of the proposed algorithm in wireless mesh networks and for different node densities. Even though node density may be traditionally harmful the proposed algorithm can exploit higher densities since nodes closer to each other create higher performance cooperative links through COOP or CPLNC.

REFERENCES

[1] K. Kumaran and L. Qian, "Uplink scheduling in CDMA packet-data systems," in *INFOCOM*, 2003.

[2] L. Tassiulas and A. Ephremides, "Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks," *IEEE Transactions on Automatic Control*, vol. 37, no. 12, pp. 1936–1949, December 1992.

[3] P. Gupta and P. Kumar, "The capacity of wireless networks," *IEEE Transactions on Information Theory*, vol. 46, no. 2, pp. 288–304, March 2000.

[4] R. Maheshwari, S. Jain, and S. R. Das, "A measurement study of interference modeling and scheduling in low-power wireless networks," in *ACM SenSys*, 2008.

[5] E. C. van der Meulen, "Transmission of information in a t-terminal discrete memoryless channel," Ph.D. dissertation, Department of Statistics, University of California, Berkeley, CA, 1968.

[6] ——, "Three-terminal communication channels," *Advances in Applied Probability*, vol. 3, no. 1, pp. 120–154, 1971.

[7] S. Zhang, S. C. Liew, and P. P. Lam, "Hot topic: Physical-layer network coding," in *MobiCom*, 2006.

[8] K. Jain, J. Padhye, V. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," in *ACM International Conference on Mobile Computing and Networking (MOBICOM)*, 2003.

[9] G. Brar, D. M. Blough, and P. Santi, "Computationally efficient scheduling with the physical interference model for throughput improvement in wireless mesh networks," in *MOBICOM*, 2006.

[10] W. Wang, Y. Wang, X.-Y. Li, W.-Z. Song, and O. Frieder, "Efficient interference-aware TDMA link scheduling for static wireless networks," in *Mobicom*, 2006.

[11] Q. Xiong, W. Jia, and C. Wu, "Packet scheduling using bidirectional concurrent transmission in wimax mesh networks," in *WiMA*, 2007.

[12] D. M. Blough, G. Resta, and P. Santi, "Approximation algorithms for wireless link scheduling with SINR-based interference," *IEEE/ACM Transactions on Networking*, 2010.

[13] W. Z. Shaohe Lv, X. Wang, and X. Zhou, "Scheduling in wireless ad hoc networks with successive interference cancellation," in *INFOCOM*, 2011.

[14] G. D. Celik, G. Zussman, W. F. Khan, and E. Modiano, "MAC for networks with multipacket reception capability and spatially distributed nodes," *IEEE Transactions on Mobile Computing*, vol. 9, pp. 226–240, 2010.

[15] X. Wang and J. J. Garcia-Luna-Aceves, "Embracing interference in ad hoc networks using joint routing and scheduling with multiple packet reception," in *INFOCOM*, 2008.

[16] C.-Y. Hong, A.-C. Pang, and P.-C. Hsiu, "Approximation algorithms for a link scheduling problem in wireless relay networks with qos guarantee," *IEEE Transactions on Mobile Computing*, 2010.

[17] O. Goussevskaia and R. Wattenhofer, "Complexity of scheduling with analog network coding," in *ACM FOWANC*, 2008.

[18] F. Xue, C.-H. Liu, and S. Sandhu, "MAC-layer and PHY-layer network coding for two-way relaying: Achievable rate regions and opportunistic scheduling," in *Allerton Conference on Communication, Control and Computing*, 2007.

[19] P. Chaporkar and A. Proutiere, “Adaptive network coding and scheduling for maximizing throughput in wireless networks,” in *Mobicom*, Montreal, Quebec, Canada, September 2007.

[20] Y. E. Sagduyu and A. Ephremides, “On joint MAC and network coding in wireless ad hoc networks,” *IEEE Transactions on Information Theory*, vol. 53, no. 10, pp. 3697–3713, October 2007.

[21] A. Argyriou and A. Pandharipande, “Cooperative protocol for analog network coding in distributed wireless networks,” *IEEE Transactions on Wireless Communications*, vol. 8, no. 10, pp. 2014–2023, October 2010.

[22] S. Katti, S. Gollakota, and D. Katabi, “Embracing Wireless Interference: Analog Network Coding,” in *SIGCOMM*, 2007.

[23] J. N. Laneman, D. Tse, and G. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, December 2004.

[24] A. Argyriou and A. Pandharipande, “Collision recovery in distributed wireless networks with opportunistic cooperation,” *IEEE Communications Letters*, vol. 14, no. 4, pp. 300–302, April 2010.

[25] D. Yang, X. Fang, N. Li, and G. Xue, “A simple greedy algorithm for link scheduling with the physical interference model,” in *IEEE Globecom*, December 2009.

[26] O. Goussevskaia, Y. V. Oswald, and R. Wattenhofer, “Complexity in geometric SINR,” in *ACM MobiHoc*, 2007.

[27] S. Ross, *Introduction to probability models*. Academic Press, 2003.

APPENDIX A
PERFORMANCE ANALYSIS OF THE GREEDY-SLS ALGORITHM

In this section we provide a performance analysis for the proposed algorithm. For a given network of N sender nodes, our goal is to calculate the probability mass function (p.m.f.) for the random variable that expresses the number of used slots by the algorithm.

Let us denote with $P_C(Q,K)$ the probability that for an arbitrary pair of source/destination nodes either the CPLNC or COOP or the Direct modes are used when Q users transmit in the broadcast phase and K transmit in the forwarding phase. Note that the definition of $P_C(Q,K)$ *gives the probability that precisely one of these modes will be used and no additional slot will be added by the SLS algorithm.* This is critical for the next expression we present. Given the above, what is the probability that T slots are actually used? The p.m.f. of this random variable T is defined as

$$P[t=T] = \sum_{\forall n_i \text{ s.t. } \sum_{i=i}^{T} n_i = N} \prod_{i=1}^{T-1} P_C(Q_i, Q_{i+1}).$$

To understand this expression, consider for example the case that the total users are $N=3$ and we want to find the probability that the number of used slots is 2. Then the above becomes

$$P[t=3] = P_C(Q_1=1, Q_2=2) + P_C(Q_1=2, Q_2=1),$$

which gives all the possible combinations of the three senders. For another example consider the case that $N = 5, T = 3$. Then we have in a more compact form that

$$\begin{aligned} P[t=3] &= P_C(1,2)P_C(2,2) + P_C(1,1)P_C(1,3) \\ &+ P_C(1,3)P_C(3,1) + P_C(2,2)P_C(2,1) \\ &+ P_C(2,1)P_C(1,2) + P_C(3,1)P_C(1,1) \end{aligned}$$

In the above expression the term $P_C(1,2)P_C(2,2)$ expresses the probability that when 1, 2, and 2 users are scheduled in three successive slots, this allocation will be successful and not additional slot will be needed.

Now we focus our attention on the calculation of $P_C(Q,K)$ and we decompose it further. Let $P_{CPLNC}(Q,K)$ denote the probability that the CPLNC mode is selected when Q users transmit in the broadcast phase and K transmit in the forwarding phase. Similar definitions can easily follow for COOP and Direct. Then, $P_C(Q,K)$ can be expressed as

$$\begin{aligned} P_C(Q,K) &= P_{CPLNC}(Q,K)[1 - P_{COOP}(Q,K)][1 - P_{DIR}(Q)] \\ &+ P_{COOP}(Q,K)[1 - P_{DIR}(Q)] + P_{DIR}(Q) \end{aligned} \tag{18}$$

Now we have to calculate each of the terms in the previous expression and this analysis for COOP is presented in the next section.

A. Transmission Mode Selection Probability

In this subsection we calculate the probability that a certain transmission mode is used over another when Q and K users interfere in the broadcast and forwarding phases. First of all, we assume that all the nodes are distributed uniformly in a square area normalized to have unit dimensions. This is realistic and also allows easier derivation of several distributions later. We also assume unit transmit power from all the senders. With the proposed algorithm a certain cooperative mode is used when the SINR is higher from another mode. More specifically the probability that CPLNC is used over COOP is equal to

$$P[snr_i^{cplnc}(Q,K) \geq snr_i^{coop}(Q,K)] \tag{19}$$

To reduce the number of manipulated random variables (R.V.), and for demonstrating the derivation process, we calculate the probability that the COOP is used over Direct and not CPLNC

over COOP. The desired probability is defined as

$$P[snr_i^{coop}(Q,K) \geq snr_i^{dir}(Q)] =$$
$$= \Big[\frac{P_i\gamma_{ii}}{\sigma^2 + I_{i,b}} \frac{P\gamma_{ir}\gamma_{ri}g^2}{\sigma^2 + I_{i,f} + (\sigma^2 + I_{r,b})\gamma_{ri}g^2} \geq \frac{P\gamma_{ii}}{\sigma^2 + I_{i,b}}\Big]$$

By substituting $I_{r,b}$ and $I_{i,f}$ and with minor algebraic manipulations the previous becomes

$$P[snr_i^{coop} \geq snr_i^{dir}]$$
$$= P[\frac{\sigma^2 + \sum_K P_k\gamma_{i,k} + (\sigma^2 + \sum_Q P_n\gamma_{r,n})\gamma_{ri}g^2}{P_i\gamma_{ir}\gamma_{ri}g^2} \leq 1\Big], \tag{20}$$

where Q and K denote the number of nodes interfering in the broadcast and forwarding phases. Now we calculate the p.d.f. of the new random variable in the expression above.

1) Numerator Derivation: Let us define first the following R.V. that corresponds to the numerator of (20):

$$U_1 = \sigma^2 + \sum_K \gamma_{i,k} + (\sigma^2 + \sum_Q \gamma_{r,n})\gamma_{ri}g^2$$

Rewriting the above it in terms of the helper distributions V_1, V_2, that are the sum of uniformly distributed i.i.d. R.Vs, we have

$$U_1 = \sigma^2 + V_1 + (\sigma^2 + V_2)V_3g^2 \quad U_2 = V_2 \quad U_3 = V_3$$

The Jacobian of the above three equations is easily derived to be $J = 1$. Also the solution to the above system is

$$\bar{v}_1 = u_1 - \sigma^2 - (\sigma^2 + u_2)u_3g^2, \quad \bar{v}_2 = u_2, \quad \bar{v}_3 = u_3.$$

So the marginal p.d.f. of U_1, that is the R.V. of interest, is

$$f_{U_1}(u_1) = \int\int f_{V_1}(\bar{v}_1)f_{V_2}(\bar{v}_2)f_{V_3}(\bar{v}_3)du_2du_3$$

$$f_{U_1}(u_1) = \int\int f_{V_1}(u_1 - \sigma^2 - (\sigma^2 + u_2)u_3g^2)f_{V_2}(u_2)f_{V_3}(u_3)du_2du_3 \tag{21}$$

We have to calculate the range of these R.Vs in the integral in order to proceed. Recall first that V_3 corresponds to γ that is uniformly distributed in [0,1]. So the last expression becomes

$$\begin{aligned} f_{U_1}(u_1) &= \int\int_0^1 f_{V_1}(u_1 - \sigma^2 - (\sigma^2 + u_2)u_3g^2)f_{V_2}(u_2)1du_3du_2 \\ &= \int\int_0^1 f_{V_1}(u_1 - \sigma^2 - (\sigma^2 + u_2)u_3g^2)f_{V_2}(u_2)du_3du_2 \end{aligned} \tag{22}$$

To calculate the previous integral we set $x = u_1 - \sigma^2 - (\sigma^2 + u_2)u_3 g^2$, and we differentiate with respect to u_3 so that $dx = -u_2 g^2 du_3$. Then (22) becomes

$$f_{U_1}(u_1) = \int \int_{u_1-\sigma^2}^{u_1-\sigma^2-(\sigma^2+u_2)g^2} f_{V_1}(x) f_{V_2}(u_2) \frac{1}{-u_2 g^2} dx du_2$$

$$f_{U_1}(u_1) = \int f_{V_2}(u_2) \frac{1}{-u_2 g^2} \int_{u_1-\sigma^2}^{u_1-\sigma^2-(\sigma^2+u_2)g^2} f_{V_1}(x) dx du_2 \tag{23}$$

To calculate the inner integral we have to be careful since R.V. V_1 is the sum of K uniform R.Vs, while similarly V_2 is the sum of N uniform R.Vs This is the Irwin-Hall distribution specified as [27]:

$$f_{V_1}(x) = \frac{1}{(K-1)!} \sum_{0 \le j \le x} (-1)^j \binom{K}{j} (x-j)^{K-1} \tag{24}$$

Let us write then the inner integral as

$$\begin{aligned} f(u_1, u_2, K) &= \int_{u_1-\sigma^2}^{u_1-\sigma^2-(\sigma^2+u_2)g^2} f_{V_1}(x) dx \\ &= \int_{u_1-\sigma^2}^{u_1-\sigma^2-(\sigma^2+u_2)g^2} \frac{1}{(K-1)!} \sum_{0 \le j \le x} (-1)^j \binom{K}{j} (x-j)^{K-1} dx \\ &= \frac{1}{(K-1)!} \sum_{0 \le j \le x} (-1)^j \frac{1}{K} \binom{K}{j} (x-j)^K \Big|_{u_1-\sigma^2}^{u_1-\sigma^2-(\sigma^2+u_2)g^2} dx \end{aligned}$$

To simplify the forthcoming expression for the inner integral we set the limits of the integrals to $x_1 = u_1 - \sigma^2, x_2 = u_1 - \sigma^2 - (\sigma^2 + u_2)g^2$. Thus,

$$f(u_1, u_2, K) =$$

$$\begin{cases} 0 & x_1 < 0 \text{ and } x_2 < 0 \\ \frac{1}{(K-1)!} \sum_{0 \le j \le x} (-1)^j \frac{1}{K} \binom{K}{j} \left[(x_2 - j)^K - (0-j)^K \right] & x_1 < 0 \text{ and } x_2 < K \\ \frac{1}{(K-1)!} \sum_{0 \le j \le x} (-1)^j \frac{1}{K} \binom{K}{j} \left[(x_2 - j)^K - (x_1-j)^K \right] & 0 < x_1 < x_2 < K \\ \frac{1}{(K-1)!} \sum_{0 \le j \le x} (-1)^j \frac{1}{K} \binom{K}{j} \left[(K - j)^K - (x_1-j)^K \right] & x_1 < K \text{ and } x_2 > K \\ 0 & x_1 > K \text{ and } x_2 > K \end{cases} \tag{25}$$

Finally, we can evaluate (23) as

$$f_{U_1}(u_1) = \int f_{V_2}(u_2) \frac{-1}{u_2 g^2} f(u_1, u_2, K) du_2$$

$$= \int_0^Q \frac{1}{(Q-1)!} \sum_{0 \le j \le u_2} (-1)^j \binom{Q}{j} (u_2 - j)^{Q-1} \frac{1}{-u_2 g^2} f(u_1, u_2, K) du_2 \tag{26}$$

2) Derivation of the Final p.d.f.: In the denominator of (20) we have the product of two uniform R.Vs with the p.d.f. of their product being $f_{\gamma_{ri}\times\gamma_{ir}}(\gamma_{ri}\gamma_{ir}) = -ln(\gamma_{ir}\gamma_{ri})$ for $\gamma_{ir}\gamma_{ri} \geq 0$.

Eventually the p.d.f. of the fraction in (20) is the p.d.f. of the fraction of the two involved R.Vs. We know that is given for two independent R.Vs X, Y as

$$f_S(s) = \int_{-\infty}^{\infty} f_X(x) f_Y(x/s) \frac{x}{s^2} dx$$

with $s = x/y$. In our case $s = \frac{u_1}{\gamma_{ir}\gamma_{ri}}$ so

$$\begin{aligned} f_S(s) &= \int f_{U_1}(u_1) f_{\gamma_{ri}\times\gamma_{ir}}(u_1/s) \frac{u_1}{s^2} du_1 \\ &= \int_0^N -f_{U_1}(u_1) ln(u_1/s) \frac{u_1}{s^2} du_1, \end{aligned} \tag{27}$$

since U_1 follows the Irwin-Hall distribution in the range [0,N]. Now the integral above can be numerically evaluated since it consists of summation terms that can be simplified for given N. This is an important results since it is p.d.f. of the ratio of SINR of the COOP mode versus the SINR of the Direct mode for a network of randomly and uniformly distributed sources, destination and relays. This essentially allows us to calculate under the proposed scheduling algorithm which transmission mode will be used. From our initial derivations, in the first subsection we can calculate the p.m.f. of the number of used slots for given total number of participating nodes N.

$greedy\_csls(\mathcal{S}, \mathcal{R})$

generate $\mathcal{U}'$
for node $i \in \mathcal{S} \bigcup \mathcal{R}$ **do**
  calc. $I_{i,\mathcal{U}'} = \sum_{l_{m,k} \in \mathcal{U}', \forall m \neq i, k \neq i} P\gamma_{m,i}$ //interf. from all others
end for
for link $l_{ii} \in \mathcal{U}$ **do**
  calc. $\mathcal{I}_i^{dir}$ according to (17), add in $\mathcal{L}$
  calc. $\mathcal{I}_{i,r}^{coop}$ according to (12) (17), add in $\mathcal{L}$
  for link $l_{jj} \in \mathcal{U}/\{l_{ii}\}$ **do**
    calc. $\mathcal{I}_{i,j,r}^{cplnc}$ according to (12) (17), add in $\mathcal{L}$
  end for
end for
calc. sensitivity for all $l \in \mathcal{L}$ as $\eta = ...$
order($\mathcal{L}$)
for link $(i, j, r) \in \mathcal{L}$ **do**
  for slot $t = 1$ until T **do**
    if $\mathcal{I}_i > I_{i,t}$ **then**
      link can be added, scheduled=TRUE
      New interference $I_{i,t} = I_{i,t} + P\gamma_{i,m} + P\gamma_{j,m}$
    else
      cannot add (i, j, k) in t, $\mathcal{Z}_t = \mathcal{Z}_t \cup l_{i,j,r}$ break;
    end if
  end for
  if scheduled=TRUE **then**
    //Checked all slots. Add (i, j, r) in the one with the minimum $I_{i,t}$
    $\mathcal{A}_t = \mathcal{A}_t \cup l_{i,j,r}$ //Remove it from non-scheduled $\mathcal{L} = \mathcal{L} - \{l_{i,j,r}, ...\}$
  end if
  if scheduled=FALSE **then**
    if (i, j, k) is CPLNC or COOP mode **then**
      $\mathcal{L} = \mathcal{L} - \{(i, j, k)\}$
    else
      T=T+1
    end if
  end if
end for